US Army Corps
of Engineers

Mississippi River Real-Time Forecast UNET Model

St. Paul District, July 1997

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10.1 St. Paul Forecast Model. The St. Paul District developed a Mississippi Basin Model System (MBMS) UNET model of the Mississippi River for real-time water control forecasting. The products of the Mississippi Basin Modeling System are used internally for the operation of Corps of Engineer projects within the St. Paul District. Experience during the 1997 flood indicated that having accurate forecasts results in cost savings in the required emergency operations. The MBMS results also provided excellent predictions with regard to the time that lock(s) are taken out of and, afterwards, placed back in operation. The following write-up discusses the geographic coverage of the model, the data sources used in the development of the model, the calibration of the model to historical flow events for low flow, navigation flow and flood flow, the operational experience using the model in a real-time forecast mode, and finally, the interaction and transfer of data between the St. Paul District model and the Rock Island district model.

10.1.1 Geographic Coverage. Hydrologic modeling was performed by the St. Paul District along the Mississippi River from Anoka, Minnesota at river mile 864.8, downstream to Dubuque, Iowa, at river mile 579.0. Even though the model extends to Dubuque, Iowa, the model is intended to provide results only for the reach at and upstream of Guttenberg, Iowa at Lock and Dam 10. Guttenberg, Iowa, corresponds with the St. Paul District boundary with the Rock Island District. The extension of the model to Dubuque allows for a convergence reach taking care of any mathematical instability or errors introduced from the downstream boundary condition. A general location map illustrating significant project features within the study reach is shown on the basin map.

10.1.1.1 Mississippi River. The headwaters of the Mississippi River are in a region of dense forests, great swamps and thousands of lakes. The river begins at the outlet of Lake Itasca at an elevation of 1463 feet above sea level, and flows north, east and then southwest through timbered landscape to Brainerd, Minnesota. It flows south from Brainerd and then to the southeast through a broad, shallow glacial outwash valley to Minneapolis-St. Paul, and the confluence of the Minnesota River. At this point, it leaves the northern woodlands and lakes and meanders southward past fertile prairies and numerous towns and cities. The river is often banked by high bluffs. The St. Croix River flows into the Mississippi River at Prescott, Wisconsin. The Mississippi River forms the boundary between Minnesota and Wisconsin below this junction. Further south, the river forms the boundary between Iowa and Wisconsin. Sixteen river miles above Lock and Dam 10 at Guttenburg, Iowa, the Wisconsin River joins the Mississippi River. The Mississippi River drops about 850 feet(almost 60 percent) of its total fall within the St. Paul District. The Mississippi River and its tributaries in the St. Paul District drain an area of almost 80,000 square miles, of which 45,000 square miles are in Minnesota, 32,000 square miles are in Wisconsin and the remainder are in South Dakota and Iowa. Between Anoka, Minnesota and Guttenberg, Iowa, the Mississippi River increases from 19,000 square miles to 80,000 square miles.

10.1.1.2 Tributaries. The major tributaries to the Mississippi River from Anoka, Minnesota to Dubuque, Iowa are described in the following paragraphs:

10.1.1.2.1 Minnesota River - RM 844.0. The source of the Minnesota River is the Little Minnesota River, which flows into Big Stone Lake, located on the Minnesota-South Dakota border. There is a low divide between it and the Red River basin to the north. During the glacial epoch, the present-day Red River and Minnesota River valleys provided drainage for glacial Lake Agassiz. Lake Agassiz was a huge body of water about 110,000 square miles in are which occupied what is now the Red River basin in Minnesota and North Dakota and parts of Ontario and Manitoba, Canada. When the glacial ice blocked the northern drainage of this lake, a tremendous volume of water passed down the present Minnesota River valley. As a results, the valley is characterized by wide flood plains which have been developed for agriculture and agricultural communities. The Minnesota River passes through a rich agricultural area and the valley bottom lands, which can be a mile or two in width, are very productive. The low, wide, flood plains and the flat slope of the basin, however, make it especially susceptible to flooding.

From Bigstone Lake, the Minnesota River flows in a southeasterly direction for about 225 miles to Mankato, Minnesota. At Mankato, the river turns abruptly to the northeast and flows another 106 miles to its mouth at St. Paul, Minnesota on the Mississippi River.

The basin consists generally of an undulating prairies region with the topography characterized by gently rolling hills separated by level outwash plains. The economy and occupations of the area are chiefly related to agriculture and agricultural-based industries. A large portion of the population is rural. The major cities are located along the main stem.

The Minnesota River drains an area of about 16,900 square miles of which nearly 90 percent is in south central Minnesota. The Minnesota River also drains 1,640 square miles in South Dakota and 370 square miles in Iowa. The basin is approximately 230 miles long and varies between 60 and 100 miles in width.

10.1.1.2.2 St. Croix River - RM 811.3 . The St. Croix River is a left bank tributary located on the Minnesota-Wisconsin border.

10.1.1.2.3 Cannon River - RM 795.7. The Cannon River is a small right bank tributary which passes through Welch, Minnesota.

10.1.1.2.4 Chippewa River - RM 763.5. The Chippewa River basin covers 9,480 square miles through its entire length, 6,630 square miles of which is upstream of Eau Claire, Wisconsin. The basin includes all or part of 19 counties in Wisconsin and Upper Michigan. The Chippewa River rises in the northern Wisconsin lake region, which includes a small part of Upper Michigan. It flows generally to the southwest across Northwestern Wisconsin to its confluence with the Mississippi River at the lower end of Lake Pepin, near Mississippi River Mile 763. The largest tributary to the Chippewa River is the Eau Claire River, which joins the Chippewa River at Eau Claire and drains an area of about 880 square miles. Other important tributaries are the Eau Galle, Red Cedar, Yellow, Jump and Flambeau Rivers. Basin topography in the upper reaches is typified by gently rolling low hills with numerous potholes , lakes, marshes and swamps. Runoff is very low in this area. In the lower reaches of the basin, the country is more hilly and consists of coulees and uplands, some of which rise to a height of 200 to 400 feet above the floodplain. There is rapid runoff from the upland areas. The overall slope of the

Chippewa River is 4 to 5 feet per mile and is controlled by a resistant crystalline bedrock surface. The flattest slopes are in the uppermost and lowermost reaches of the basins. In the uppermost reaches, including the Flambeau-Manitowash headwater system, drainage is through a glacial outwash plain. Here the slope is only 1.3 feet per mile. In the lower reach, below Eau Claire, the river has a uniform slope of about 1.5 feet per mile and meanders broadly over its 1-to-2 mile wide floodplain. Over the middle reaches, the river has an average slope of about 5.8 feet per mile. This part of the river is characterized by numerous rapids and falls which create locally steep-sloped areas. Dams and impoundments, primarily for generating electric power, are located at a number of these steep gradient reaches. Many rapids, however, remain untouched, their primary uses being recreational. About 75 percent of the land in the basin consists of deciduous and coniferous forest, and wetland. The remainder, mostly in the lower reaches, is cropland,. Major land uses are recreation, forest management, and agriculture. In the north, forests provide wood harvesting and related manufacturing and, along with the lakes and streams, offer recreation opportunities. Agriculture is dominant in the south.

10.1.1.2.5 Zumbro River - RM 750.3 . The drainage basin in the upper reaches of the Zumbro River is gently undulating agricultural land. East of Rochester the watershed area is a plateau-like surface dissected by narrow, steep-walled gorges and by tributary coulees, hollows, or ravines. Rochester is located in a bowl-shaped valley about 2 miles in diameter surrounded by bluffs cut by the valleys of the South Fork and its tributaries at that point. Beginning in the Rochester area and extending downstream the river valleys become sharply defined and the adjacent rock walled bluffs rise on steep gradients to heights of 100 to 200 feet above the valley floor. At Zumbro Falls, Minnesota, about 24 miles west of the mouth of the river, the valley floor is about 160 feet below the uplands and approximately one-eight of a mile wide. Between Zumbro Falls and Kellogg, the upland areas are as much as 500 feet above the valley floor, which in several places is a mile wide. Near Kellogg, the Zumbro River leaves a well-defined valley and crosses a wide, gently sloping area before entering the Mississippi River. Average elevations vary from about 1,300 feet in the upland areas south of Rochester to about 1,000 feet at Rochester and 680 feet near the junction of the Zumbro and the Mississippi Rivers. Other than some small marsh-type impoundments, there are no natural lakes in the basin.

10.1.1.2.6 Trempealeau River - RM 716.2. The Trempealeau River basin covers an area of about 750 square miles located in west central Wisconsin about midway between the Cities of La Crosse and Eau Claire. Its basin characteristics are very similar to those of the Buffalo River. The main stem rises about nine miles east of Hixton, Wisconsin, about 84 miles above the confluence with the Mississippi River. It then flows in a generally westerly direction to Independence, Wisconsin, thence to the south to join the Mississippi River near River Mile 716. The entire drainage area of the Trempealeau River lies within the unglaciated driftless area. Surface elevations range from about 1,360 feet in the headwaters to about 650 feet in the vicinity of the Mississippi River confluence. The uplands are deeply dissected into rugged ridges and rounded hills. Covered by relatively impervious soils, the steep slopes allow for rapid runoff of surface waters. The broad valley of the Trempealeau River is the result of lateral erosion by the meandering stream. The general slope of the Trempealeau River ranges between 3 and 4 feet per mile. There are steeper slopes in the headwaters of the basin, as much as 30 feet per mile in the uppermost reaches above Hixton. These increase the average slope of the stream, based on a total fall of 555 feet in 84 miles, to about 6.5 feet per mile. The river is free flowing throughout its length. Land use in the basin is primarily agricultural, with steeper sloped areas kept mainly in woodlot.

10.1.1.2.7 Black River - RM 708.7 . The Black River is one of five principal tributaries to the Mississippi River above La Crosse whose course and drainage basins are entirely within the state of Wisconsin. It drains an area of 2,080 square miles above Galesville, Wisconsin, near its confluence with the Mississippi River, and 1,290 square miles above the Hatfield Dam near Black River Falls, Wisconsin. The river drains at least part of seven Wisconsin counties: Taylor, Clark, Jackson, Monroe, Trempealeau and La Crosse. Upstream of Black River Falls, the river flows through a region of flat to gently rolling terrain in a previously glaciated area. The drainage network is young and mainly postglacial, and valleys are shallow. There are widespread swampy areas east of Black River Falls. Compared to the upper reaches of other river systems in the region, the slope of the Black River is relatively mild and uniform, at about 6 feet per mile, in this area. This is due to the presence of a crystalline bedrock substrate which has limited downcutting. After passing Black River Falls, the river enters the unglaciated "driftless area," an area characterized by deeply cut valleys, or coulees, above which are areas of relatively uniform tableland. Here the river flows in a meandering manner through a thick alluvial fill at a slope of about 2 feet per mile to its confluence with the Mississippi River at La Crosse, Wisconsin near Mississippi River mile 699. There are two impoundments on the Black River: Lake Arbutus, formed by the Hatfield Dam; and an unnamed impoundment formed by the Black River Dam in Black River Falls. Land use in the basin is predominately agricultural, with some recreational use around Lake Arbutus and along parts of the main Black River channel.

10.1.1.2.8 South Fork of the Root River. The South Fork of the Root river is a small tributary to the Root River within the Root River basin which is described in the next paragraph.

10.1.1.2.9 Root River - RM 693.8. The Root River Basin is located in the southeastern portion of Minnesota. The basin has a drainage area of 1630 square miles and is elliptical in shape with a length of approximately 77 miles and a width of approximately 34 miles. The basin encompasses all or portions of Houston, Olmsted, Fillmore, and Moweer counties. The basin's major watercourse is the Root River. The Root River has steep slopes in the upper reaches of the basin and mild slopes near its confluence with the Mississippi River. The river passes through incorporated areas as well as large expanses of agricultural areas. A number of the communities in the upper reaches of the basin are flash flood prone.

10.1.1.2.10 Upper Iowa River - RM 671.0. The Upper Iowa has its source in the southeast corner of Mower County, Minnesota. It flows in a southeasterly direction to Decorah, Iowa. It then flows in an easterly direction, entering the flood plain of the Mississippi about 1.5 miles south of New Albin, Iowa. The total drainage area of the Upper Iowa River is about 1,020 square miles and includes parts of Allamakee, Winneshiek, Howard, and Mitchell Counties of northeastern Iowa, and small areas along the southern boundaries of Houston, Fillmore, and Mower Counties in southeastern Minnesota.

10.1.1.2.11 Kickapoo River. The Kickapoo River rises in Monroe County in southwestern Wisconsin and flows southwest through Vernon, Richland, and Crawford Counties. The river empties into the Wisconsin River near Wauzeka, about 16 miles upstream from the junction of the latter stream with the Mississippi River. The basin of the Kickapoo River includes about 776 square miles and is about 60 miles long and 10 to 15 miles wide. The largest tributaries are the West Fork, Taintor Creek, Morris Creek, and Billings Creek.

The topography of the basin is comparatively rugged, consisting of narrow ridges and deep valleys. The ridge crests, which are distinctly round-topped, are 0.1 to 0.6 mile wide. The valley bottoms are 0.1 to 1.0 mile in width and are 300 to 400 feet below the upland level. The summits of the ridges generally slope southward with the dip of the rock strata.

10.1.1.2.12 Wisconsin River - RM 631.0. The Wisconsin River has an elongated drainage area of 12,200 square miles. It rises in Lac Vieux Desert, on the Wisconsin -Michigan Upper Peninsula border.

From this point it flows in a generally north to south direction, winding through heavily forested lands, agricultural lands, and then the rolling hills and bluffs of southwestern Wisconsin to its confluence with the Mississippi River at Prairie du Chien, Wisconsin, near Mississippi River Mile 631. The United States Geological Survey divides the Wisconsin River basin into three sections. These are: the upper basin, which is between the source at Lac Vieux Desert and Merrill, Wisconsin; the central basin, which extends from Merrill to Wisconsin Dells; and the lower basin, which extends from Wisconsin Dells to the confluence with the Mississippi River.

The drainage area of the upper Wisconsin River basin is about 2,780 square miles, including parts of six counties. The terrain varies form flat glacial outwash plains to hilly ground moraines. Most of the upper basin is made up of the flat outwash with a gentle slope and many shallow depressions occupied by lakes or bogs. Vegetation is mostly deciduous or coniferous forest except in boggy areas. There is very little runoff from this area. South of the Oneida County line, the rerrain becomes more varied, and runoff increases. About half of this area is forest or pastured woodlot and has many lakes and bogs. The slope of the river through the upper basin is fairly uniform at 3.5 feet per mile. Principal tributaries in this reach are the Pelican, Tomahawk, Spirit, and Prairie Rivers. There are a number of impoundments both on the main stem and the tributaries. These are used for water supply, recreation and some hydropower.

The drainage area of the central Wisconsin River basin is about 5,050 square miles, including parts of 12 counties. Here the river flows through an extensive sand plain. Most of the terrain is flat to gently sloping, with a few isolated large hills such as Rib Mountain, near Wausau. Like the upper basin, there are a number of large, flat, boggy depressions. Some of these have no surface outlets, and are thus closed off from the rest of the river system in this way. Over 50 percent of the land in this area is used for agriculture. There is recreational and some hydropower use along the streams and impoundments. The slope of the river through the central basin averages 3.3 feet per mile from Merrill to Petenwell Lake, and 1.7 feet per mile from Petenwell Lake to Wisconsin Dells. Principal tributaries in this reach are the Rib, Eau Claire, Big Eau Pleine, Little Eau Pleine, Yellow, and Lemonweir Rivers. There are 14 impoundments on this reach of the Wisconsin River, the largest of which are Lake Dubay, between Stevens Point and Wausau, and Petenwell and Castle Rock Lakes, which are located, one immediately flowing into the other, between Wisconsin Rapids and Wisconsin Dells.

The remainder of the Wisconsin River basin, an area of about 4,450 square miles, comprises the lower basin. Here the terrain is hilly; there was no glaciation in this area to level it out, as in the central and northern areas. There is high runoff in this area. Most of this portion of the basin is used for agriculture, except for the steeper slopes which have been retained mostly in wood lots, and the waterways which are used for recreation and some hydropower. The river channel meanders through its alluvium-filled valley at an average slope of about 1.5 feet per mile. The river has two major tributaries in this part of the basin, the Baraboo and Kickapoo Rivers. There is one last impoundment on the river before it flows unimpeded to its confluence with the Mississippi River. This is Lake Wisconsin, just downstream of Portage.

10.1.2.1 Unet Application - Geographic Extent, Key Locations, Gages and Data Sources. The model extends from Anoka, Minnesota at river mile 864.8 to Dubuque, Iowa at river mile 579.0. A diagram of the model is shown in Figure 10.1-1. The original cross-section model was developed by the St. Paul District in 1995. The model consists of 29 reaches. Principal tributaries of the Mississippi River are modeled from the last rated gages to their mouths. The cross-sections for the Mississippi River were obtained from an HEC-2 model that was developed in 1981. The cross-sections for the Minnesota River, the South Fork Root River, the Root River, the Kickapoo River, and the Wisconsin River were surveyed cross-sections, obtained from flood plain insurance studies. The cross-sections for the other tributaries were measured from USGS 15 Minute Quadrangle maps. The elevations of cross-sections and structures were all converted to the 1929 or NGVD datum to be consistent with the models of the Mississippi River built by other Districts.

The limits of the cross-section property tables along the Mississippi River were set by navigation pool. The limits on the property tables are shown in Table 10.1-1.

Table 10.1-1

Limits on the Cross-Section Property Tables for the Mississippi River

Location	Tailwater River Mile	Reaches	Pool Elevation (Feet)	Starting Elevation (Feet)	Table Height (Feet)	Maximum Elevation (Feet)	Interval (Feet)
Upper St. Anthony Falls	853.85	1	798.7	795	50	845	2.5
Lower St. Anthony Falls	853.23	1	749.5	745	60	805	3
Lock & Dam 1	847.5	1	724.6	720	60	780	3
Lock & Dam 2	815.05	1	686.7	680	45	725	2.25
Lock & Dam 3	796.91	3,4	674.5	665	40	705	2
Lock & Dam 4	752.6	7,9	666.5	655	40	695	2
Lock & Dam 5	738.12	9,11	659.5	646	40	686	2
Lock & Dam 5A	728.5	11	650.5	639	40	679	2
Lock & Dam 6	714.29	11,13	645	633.5	40	673.5	2
Lock & Dam 7	702.47	13,15	638.5	627	40	667	2
Lock & Dam 8	679.24	15,19	630.5	620.5	40	660.5	2
Lock & Dam 9	647.92	19,21	619.5	609.5	40	649.5	2
Lock & Dam 10	681.5	21,25	610.5	600.5	40	640.5	2

The starting elevations of the property tables for the tributaries were set at one foot above the invert elevation of the cross-section, the default for the UNET program. The maximum elevations of the property tables were set at 60 feet above the starting elevations.

The limits of the property tables are important factor in the accuracy of the UNET program. If the computed water surface is either above or below the property table, the program extrapolates the cross-section property (area, conveyance, etc.). The extrapolation may be in error. Whenever the program extrapolates at a cross-section, the program issues a warning message in the output file and the modeler should adjust the property tables to prevent the extrapolation.

10.1.2.2 Gages and Data Sources. Flow and stage data is required to provide the boundary conditions that drive the model. For historic simulations, inflow data for the model are from the records at the USGS gaging stations and the boundary stages are from the records of the St. Paul District. For the forecast simulation, the inflow data was computed from real-time stages applied to rating curves and the boundary stages are from the real-time stages.

10.1.2.2. USGS Flow. The U.S. Geological Survey compiles flow data at the gaging stations listed in Table 10.1-2. Flow data from these stations were collected for the period from 1964 through 1994 and stored in the file USGS.DSS for the model development.

Table 10.1-2

USGS Stream Gages		
Stream	**Station**	**River Mile**
Mississippi River	Anoka	864.8
Mississippi River	St. Paul	839.3
Mississippi River	Winona	725.6
Mississippi River	McGregor	633.6
Minnesota River	Jordan	39.4
St. Croix River	St. Croix Falls	52.2
Cannon River	Welch	12.3
Chippewa River	Durand	17.6
Zumbro River	Zumbro Falls	47.5
Trempealeau River	Dodge	8.9
Black River	Galesville	13.8
South Fork Root River	Houston	3.7
Root River	Houston	18.5
Upper Iowa River	Dorchester	18.1
Kickapoo River	Steuben	20.5
Wisconsin River	Muscoda	92
Turkey River	Garber	19.9
Grant River	Burton	9.1

10.1.2.3 Observed Stage Data. Observed stage data is collected for the Mississippi River stations listed in Table 10.1-3 and for the tributary stations listed in Table 10.1-4. For the historic period from 1964 through 1994, the daily data is stored in the file HISTMISS.DSS for the model development. For the forecast period, from October 1, 1995 through July 31, 1996, the one hour stage were collected from the real-time data base of the St. Paul Districts water control center and the stages were stored in the file WCMISS.DSS for the model development.

Figure 10.1-1

Diagram of the Mississippi River Model

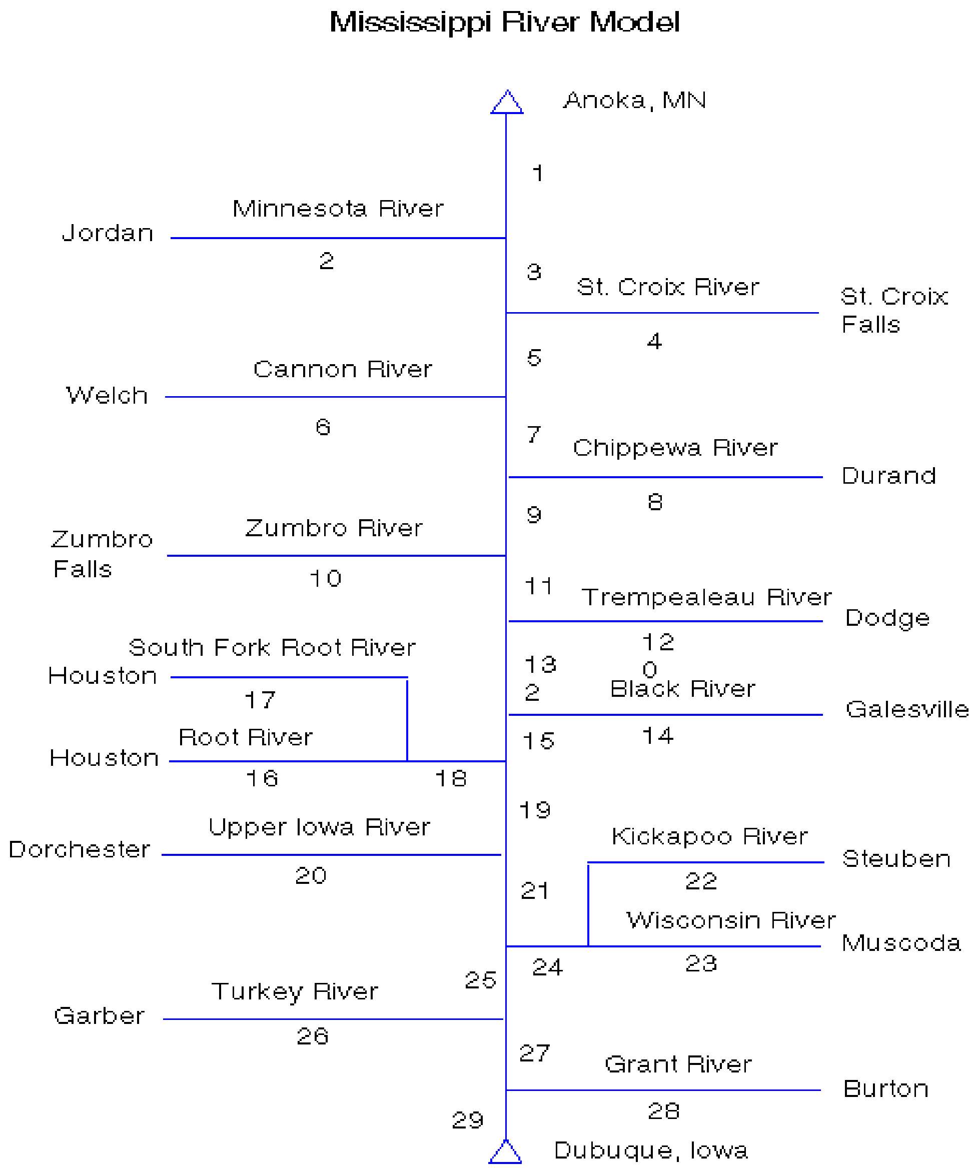

Table 10.1-3

Mississippi River Gaging Stations		
Station Name	**River Mile**	**Station Code**

Anoka	864.8	ANKM5
Upper St. Anthony Falls Headwater	853.9	USAFHW
Upper St. Anthony Falls Tailwater	853.9	USAFTW
Lower St. Anthony Falls Headwater	853.3	LSAFHW
Lower St. Anthony Falls Tailwater	853.2	LSAFTW
Lock and Dam 1 Headwater	847.6	LD1HW
Lock and Dam 1 Tailwater	847.5	LD1TW
St. Paul	839.3	STPM5
South St. Paul	833.7	SSPM5
Lock and Dam 2 Headwater	815.2	LD2HW
Lock and Dam 2 Tailwater	815.1	LD2TW
Prescot	811.0	PREW3
Lock and Dam 3 Headwater	796.9	LD3HW
Lock and Dam 3 Tailwater	796.9	LD3TW
Lake City	772.5	LKCM5
Wabasha	760.5	WABM5
Lock and Dam 4 Headwater	753.0	LD4HW
Lock and Dam 4 Tailwater	752.6	LD4TW
Lock and Dam 5 Headwater	738.3	LD5HW
Lock and Dam 5 Tailwater	738.1	LD5TW
Lock and Dam 5A Headwater	728.5	LD5AHW
Lock and Dam 5A Tailwater	728.5	LD5ATW
Winona	725.6	WNAM5
Lock and Dam 6 Headwater	714.3	LD6HW
Lock and Dam 6 Tailwater	714.3	LD6TW
Dakota	707.2	DKTM5

Lock and Dam 7 Headwater	702.6	LD7HW
Lock and Dam 7 Tailwater	702.5	LD7TW
LaCrosse	696.7	LACW3
Brownsville	689.0	BRWM5
Lock and Dam 8 Headwater	679.4	LD8HW
Lock and Dam 8 Tailwater	679.2	LD8TW
Lansing	663.0	LNSI4
Lock and Dam 9 Headwater	648.1	LD9HW
Lock and Dam 9 Tailwater	647.9	LD9TW
McGregor	633.6	MCGI4
Clayton	624.8	CLAI4
Lock and Dam 10 Headwater	615.2	LD10HW
Lock and Dam 10 Tailwater	614.9	
Cassville	606.3	
Waupeton	599.9	
Spechts Ferry	592.3	
Lock and Dam 11 Headwater	583.0	
Lock and Dam 11 Tailwater	582.6	
Dubuque	579.3	

Table 10.1-4

Tributary Gages				
Stream	**Station**	**Station Code**	**River Mile**	**Datum**
Minnesota River	Jordan	JDNM5	39.4	690.00
St. Croix River	St. Croix Falls	SCFW3	52.2	689.94
Cannon River	Welch	WCHM5	12.3	699.16
Chippewa River	Durand	DURW3	17.6	694.59
Zumbro River	Zumbro Falls	ZUMM5	47.5	811.26
Trempealeau River	Dodge	DDGW3	8.9	661.42
Black River	Galesville	GALW3	13.8	658.43
South Fork Root River	Houston	HUSM5	3.7	680.41
Root River	Houston	HOUM5	18.5	667.00
Upper Iowa River	Dorchester	DCHI4	18.1	660.00
Kickapoo River	Steuben	STEW3	20.5	657.00
Wisconsin River	Muscoda	MUSW3	92	666.77
Turkey River	Garber		19.9	
Grant River	Burton		9.1	

10.1.2.4 Rating Curves. For the forecast model, the flow from the tributaries must be estimated from the observed stages. The flow at a station is computed by applying the stages to a rating curve. The St. Paul District rating curves for the tributary gages are in the model development file NCS-RTG.DSS. The MBMS graphical user interface filename is ncs-mi-ratings.dss. The rating curves were obtained from the U.S. Geological Survey.

10.1.2.5 Navigation Dams. The reach which was modeled contains 13 navigation dams which are regulated to maintain navigation pools. The navigation dams are listed in Table 10.1-5. The upper three navigation pools behind the Upper St. Anthony Falls Dam, the Lower St. Anthony Falls Dam, and Lock and Dam 1 were simulated by rating curves at the structure. The lower 10 navigation dams are simulated according to operating rules that were presented in the Water Control Manuals for the Dams 2 through 10 (St. Paul District, 1972). Each dam is regulated according to a hinge pool procedure which attempts to maintain a control point at stages given by a rating curve. The operating rule is a rating curve of flow versus stage which, through experience, has been shown to maintain the proper stage at the control point. A sample operating rule for Lock and Dam 10 is shown in Figure 10.1-2.

The UNET program was modified (*Barkau, 1996*) to simulate navigation dams according to the operating rules. The program allows the operating rules to vary according to the seasons. Figure 10.1-3 shows the entry of the operating rule for Lock and Dam 10. The ND card defines the navigation dam. The first set of NR cards defines the operating rule for the summer. The second set of NR card defines the operating rule for the winter. The operating rules accurately simulated the operation of the navigation dams during the warm season. However, after reviewing the pool hydrographs, the dams were operated in a different manner during the winter months. For example, a constant winter pool stage of 610.5 feet NGVD no matter what the flow adequately reproduced the pool stages at Lock and Dam 10.

Table 10.1-5

Mississippi River Navigation Dams		
Location	**Tailwater River**	**Pool Elevation (Feet NGVD)**
Upper St.Anthony Falls	853.9	798.7
Lower St.Anthony Falls	853.2	749.5
Lock & Dam 1	847.5	724.6
Lock & Dam 2	815.1	686.7
Lock & Dam 3	796.9	674.5
Lock & Dam 4	752.6	666.5
Lock & Dam 5	738.1	659.5
Lock & Dam 5A	728.5	650.5
Lock & Dam 6	714.3	645
Lock & Dam 7	702.5	638.5
Lock & Dam 8	679.2	630.5
Lock & Dam 9	647.9	619.5
Lock & Dam 10	681.5	610.5

Figure 10.1-2

Operating rule for Lock and Dam 10.

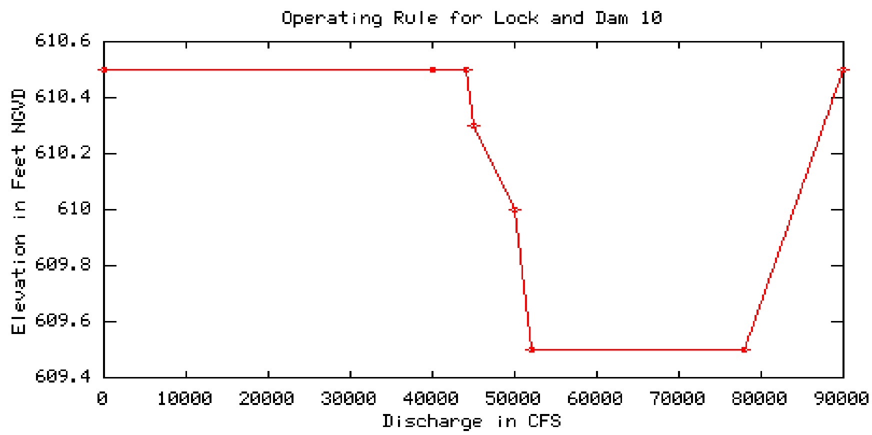

Figure 10.1-3.

Entry of the operating rule for Lock and Dam 10 into the cross-section file. All elevations are in NGVD.

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NH  6820    .000      .0    .000      .0    .000      .0    .000      .0    .000
* LOCK AND DAM NO. 10 HW
X1615.20      36      .0  1210.0   520.0     520.0     .00    0.00        0
Z0   -.5
OH HISTMISS://DAM10-POOL/ELEV/01JAN1989/1DAY//
HY LD10HW
KR \SPMISS\RC\HSPMS:/MISSISSIPPI RIVER/DAM10_POOL/STAGE-FLOW/65 & 90 TO
94//OBS/
GR629.50      .0  591.00      .0  590.80    10.0  580.80    60.0  583.00   150.0
GR581.30   235.0  579.30   270.0  578.60   355.0  583.50   435.0  582.50   475.0
GR587.20   555.0  588.20   710.0  586.50   750.0  588.00   830.0  585.80   900.0
GR585.20   970.0  595.00  1125.0  590.10  1170.0  600.50  1210.0  602.30  1350.0
GR603.10  1505.0  599.50  1660.0  600.10  1720.0  603.50  1820.0  599.50  1855.0
GR599.50  2250.0  604.50  2280.0  604.50  2510.0  599.50  2550.0  599.50  2750.0
GR604.50  2780.0  604.50  4980.0  604.50  5680.0  599.50  5690.0  599.50  6700.0
GR629.50  6820.0     .00      .0     .00      .0     .00      .0     .00      .0
KR OFF
```

```
* L&D 10; POOL STAGE = 610.5
* R.M. 615.1
ND                 610.5                                    -.2        L&D10
* OPERATING RULE FOR SUMMER; NORMAL POOL IS 610.5
NR     8   610.5       0   610.5   40000   610.5   43000   610.5   45000  610.35
NR 50000     610   52500   609.5   78000   609.5   89000   610.5
* OPERATING RULE FOR WINTER; NORMAL POOL IS 610.0
NR     2   610.0       0   610.0   89000   610.0
* SUMMER SEASON IS FROM 01APR TO 28NOV AND THE WINTER SEASON IS
* FROM 01DEC TO 28MAR WITH TRANSITIONS IN BETWEEN.
NZ  28MAR 610.0   01APR 610.5  28NOV 610.5   01DEC 610.0
*
* POOL 11  POOL ELEVATION 603.00
*
*  STARTING ELEV IN PROP TABLE = ELSTRT - RISE = 598
*           RISE  ELSTRT
XK            50     648            2.25
XI    1

NH     6   0.040    5620   0.100    8900   0.040    9340   0.070   10000   0.028
NH 11050   0.120 13500.0   0.000     0.0   0.000     0.0   0.000     0.0   0.000
X1 614.9      40 10000.0 11050.0  1000.0  1000.0  1000.0    0.00    0.00       0
Z0   -.5
OH HISTMISS://DAM10-TAIL/ELEV/01JAN1989/1DAY//
HY L&D 10 TW
KR \SPMISS\RC\HSPMS:/MISSISSIPPI RIVER/DAM10_TW/STAGE-FLOW/65 & 90 TO 94//OBS/
GR650.00  4200.0  630.00  4250.0  620.00  4400.0  615.00  4450.0  604.00  4500.0
GR595.00  4600.0  595.00  5500.0  604.00  5620.0  612.00  5650.0  612.00  5920.0
GR610.00  6000.0  610.00  6250.0  610.00  6470.0  610.00  6700.0  612.00  6710.0
GR612.00  7650.0  606.00  7700.0  604.00  7720.0  600.00  7850.0  604.00  7940.0
GR606.00  7950.0  606.00  8020.0  608.00  8050.0  608.00  8220.0  608.00  8610.0
GR606.00  8880.0  604.00  8900.0  600.00  9000.0  600.00  9300.0  604.00  9340.0
GR608.00  9350.0  608.00  9650.0  606.00  9950.0  604.00 10000.0  586.00 10200.0
GR586.00 10900.0  604.00 11050.0  620.00 12600.0  630.00 13400.0  650.00 13500.0
```

10.1.3 Calibration. The model was calibrated to reproduce water years 1965 and 1993. The model was calibrated to reproduce low to moderate stages in 1993. The model was adjusted to reproduce the higher stages in 1965 which contained the flood of record. Ungaged lateral inflow into the model was estimated using the null interior boundary condition. The base calibration for the model used rating curves which were derived from the historic record. The final calibration used discharge conveyance factors. The model was further verified against the period from water years 1991 through 1994. The model also simulated a forecast period from October 1, 1995 through July 31, 1996. During the forecast period the tributary inflow was computed by applying observed stages to rating curves. The procedure simulates forecast operation.

10.1.3.1 Null Interior Boundary Conditions. A significant problem with any unsteady flow model is the estimation of ungaged lateral inflow in the study reach. Table 10.1-6 is a drainage area summary of the reach between Anoka and Lock and Dam 10. Within this reach, 10,979 square miles of drainage area is ungaged. If runoff from this area is not included in the model, the model will by default reproduce lower stages than the prototype.

Table 10.1-6

Drainage Area Accounting							
Mississippi River			Tributaries				
Station	River Mile	Drainage Area (Sq Mi)	River Name	Mississippi River Mile	Last Downstream Station	Drainage Area (Sq Mi)	Ungaged Drainage (Sq Mi)
Anoka (USGS)	864.8	19,087					
			Minnesota	844.0	Mankato	14,900	
L&D 1	847.6	19,700					
St Paul (USGS)	839.3	36,800					2,813
L&D 2	815.2	37,000					
Prescott (USGS)	811.4	44,800					
			St Croix	811.3	St Croix Falls	5,930	
L&D 3	796.9	45,170					
			Cannon	795.7	Welch	1,480	
			Chippewa	763.6	Durand	9,010	
L&D 4	752.8	57,100					
			Zumbro	750.1	Zumbro Falls	1,130	
L&D 5	738.1	58,845					
L&D 5A	728.5	59,105					
Winona (USGS)	725.7	59,200					4,850
			Trempealeau	717.1	Dodge	643	
L&D 6	714.4	60,030					
			Black	707.8	Galesville	2,080	
L&D 7	702.5	62,340					

			South Fork Zumbro		Houston		
			Root	693.7	Houston	1,270	
L&D 8	679.2	64,770					
			Upper Iowa	671.4	Dorchester	991	
L&D 9	647.9	66,610					
McGregor (USGS)	633.4	67,500					
			Kickapoo		Steuben		
			Wisconsin	631.0	Prairie du Sac		
L&D 10	615.1	79,370					

There are three procedures for estimating ungaged inflow:

- **Index gages.**The flow record at a similar drainage basin is multiplied by a factor to simulate the flow from the ungaged area.

- **Hydrologic model.** Observed rainfall and snowmelt is applied to a hydrologic model of the ungaged area and the runoff is computed.

- **Null interior boundary condition** (*Barkau, 1995*). Ungaged inflow is computed from an observed stage applied at a repeated upstream and downstream cross-sections. The inflow is the difference between the routed flow from upstream and the computed flow downstream.

For the St. Paul model, the first two procedures are impractical. The writer could not find any index gages that could be used to estimate ungaged inflow. Furthermore, no hydrologic model exists for the ungaged area of the Mississippi River. Therefore, by default, the null interior boundary condition must be used.

The null interior boundary condition applies a stage hydrograph at a repeated cross-section. By applying the stage hydrograph the model effectively divides the river into an upstream reach and a downstream reach. The stage hydrograph at the upstream cross-section is a downstream boundary condition for the upstream reach. The flow at the upstream cross-section is the routed flow from upstream. The stage hydrograph at the downstream condition is the upstream boundary for the downstream reach. If the model is properly calibrated, the flow hydrograph at the downstream cross-section is the correct flow at the cross-section. The ungaged inflow is the difference between the flow hydrograph at the downstream cross-section and the flow hydrograph at the upstream cross-section. The key to the usage of the null interior boundary condition is the quality of the models calibration. To verify the calibration, the null interior boundary condition is applied only at USGS gaging stations where a flow record is available.

The quality of calibration is judged by the ability of the model to reproduce the USGS flow record.

The Mississippi River model is broken into four reaches - from Anoka to St. Paul, from St. Paul to Winona, from Winona to McGregor, and from McGregor to Dubuque. Null interior boundary conditions are applied at St. Paul, Winona, and McGregor. No ungaged inflow is estimated downstream of McGregor. The ungaged inflow hydrographs for the three upstream reaches was distributed uniformly according to distance along the Mississippi River. Table 10.1-7 shows manner in which ungaged inflow was distributed uniformly between Anoka and McGregor.

Table 10.1-7

Distribution of Uniform Lateral Inflow from Ungaged Areas						
Reach Number	**Reach Description**	**Upstream River Mile**	**Downstream River Mile**	**Weighting Factor**	**DSS Part B Pathname**	**Ungaged Drainage Area (Sq Mi)**
1	Anoka to Minnesota River	864.80	844.10	0.812	ANKM5 TO STPM5	
3	Minnesota River to St Paul	844.10	839.31	0.118	ANKM5 TO STPM5	2,813
3	St Paul to St Croix River	830.30	811.31	0.246	STPM5 TO WNMA5	
5	St Croix River to Cannon River	811.30	795.71	0.137	STPM5 TO WNMA5	
7	Cannon River to Chippewa Falls	795.70	763.31	0.283	STPM5 TO WNMA5	
9	Chippewa River to Zumbro River	763.60	750.11	0.119	STPM5 TO WNAM5	

11	Zumbro River to Winona	750.10	725.71	0.215	STPM5 TO WNAM5	
11	Winona to Trempealeau River	725.70	717.11	0.093	WNAM5 TO MCGI4	
13	Trempealeau River to Black River	717.10	707.81	0.101	WNAM5 TO MCGI4	
15	Black River to Root River	707.80	693.71	0.153	WNAM5 TO MCGI4	
19	Root River to Upper Iowa River	693.70	671.41	0.242	WNAM5 TO MCGI4	
21	Upper Iowa River to McGregor	671.40	633.41	0.412	WNAM5 TO MCGI4	3,316
21	McGregor to Wisconsin River	633.40	631.01			
25	Wisconsin River to Turkey River	631.00	608.21			
27	Turkey River to Grant River	608.20	593.31			
29	Grant River to Dubuque	593.31				

The procedure for estimating ungaged inflow is as follows:

1. Simulate the model with the stage hydrographs at the null interior boundary conditions at St. Paul, Winona, and McGregor.
2. Subtract the downstream and upstream hydrographs using the DSSMATH program and the input macro QSLAT.IN in the model development phase. For the graphical user interface the macro file is called null-bc-math.mac.
3. Remove the observed stage hydrographs at the null interior boundary conditions and apply the

ungaged lateral inflow.

The computations for water year 1993 at Winona will be used to demonstrate the null interior boundary condition. Figure 10.1-4 compares the computed flow hydrograph and the USGS observed flow hydrograph at Winona. The agreement is nearly exact. Figure 10.1-5 compares the routed flow hydrograph from upstream with the computed flow hydrograph downstream. The difference is the ungaged lateral inflow. Finally, Figure 10.1-6 compares the routed flow hydrograph upstream and the USGS flow hydrograph after the observed stages have been released and the input of the ungaged inflow. The agreement is once again nearly exact.

The null interior boundary condition was used to calculate inflow for water years 1965 and 1991 through 1994 and for the period from October 1, 1995 through July 31, 1996.

Figure 10.1-4

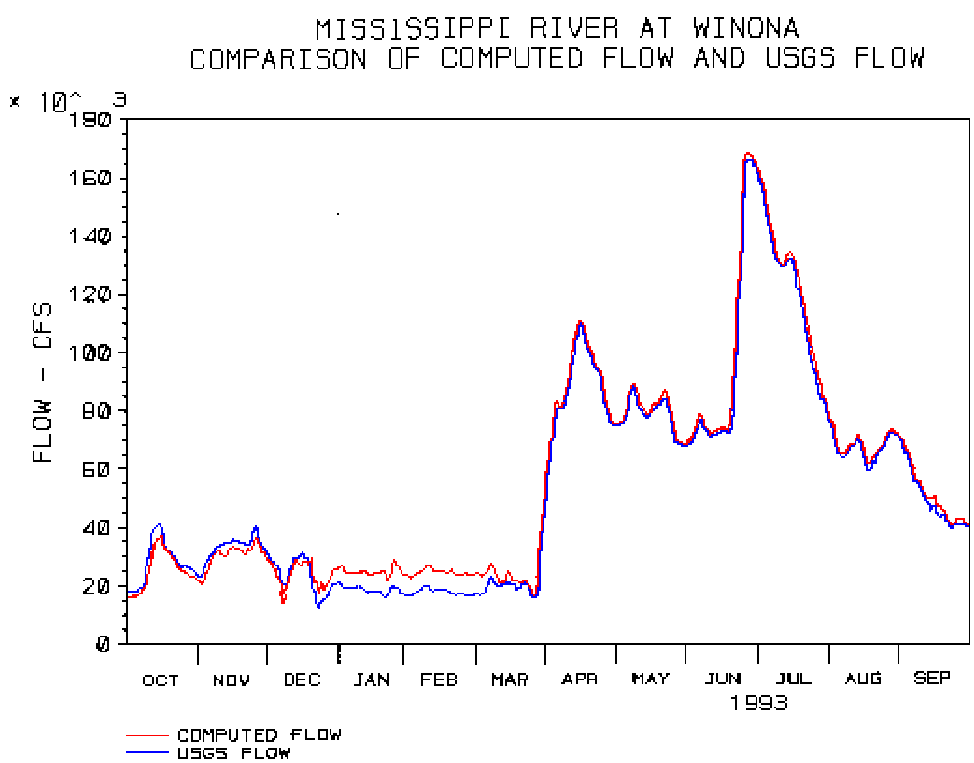


Figure 10.1-5

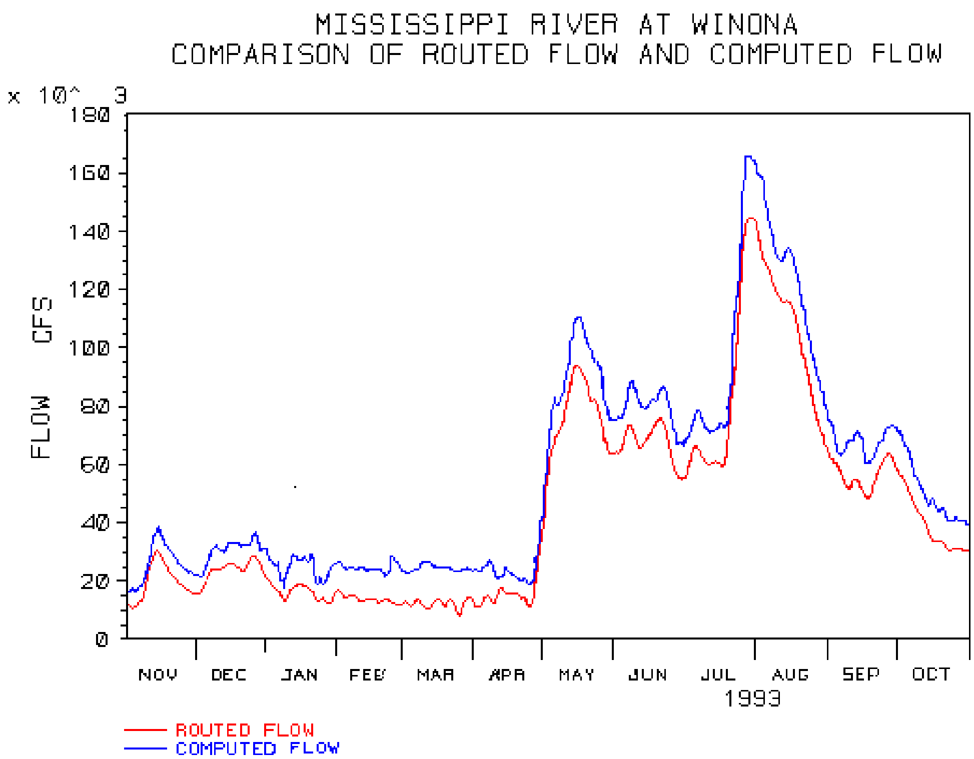
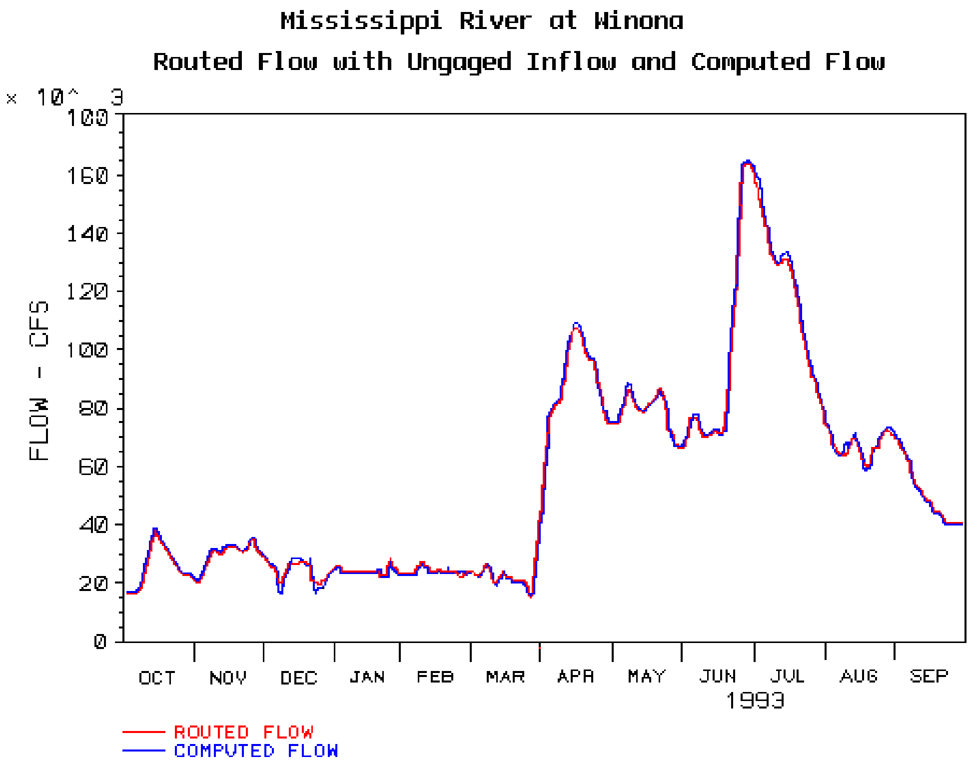


Figure 10.1-6



10.1.3.2 Base Calibration. For base calibration, the model was calibrated to reproduce rating curves at the principal gaging stations along the Mississippi River. The rating curve calibration technique is described in the report "Rating Curve Calibration" (*Barkau 1994*). Rating curves are entered at principal gaging stations. The program adjusts the conveyance of the cross-sections between the gaging stations so that the rating curve at the upstream stations is exactly reproduced by backwater calculations.

For the St. Paul model, the steps in the rating curve calibration are as follows:

1. Estimate rating curves at St. Paul, Winona, and McGregor from observed stage and USGS flow for water years 1965 and 1990 through 1993. Figure 10.1-7 shows the rating curve and the scatter diagram at Winona.

2. Estimate rating curves at the dams from stage and computed flow for calendar years 1965 and 1990 through 1994. The computed flow data were calculated by the St. Paul District Water Control Center. Figure 10.1-8 shows the rating curve and the scatter diagram at Lock and Dam 5.

3. Simulate water years 1965 and 1993.

4. Adjust the rating curves used for calibration to reproduce the USGS flow at St. Paul, Winona, and McGregor and to reproduce the observed stages at the dams.

5. Repeat steps 3 and 4 until the best reproduction of flow and observed stages was attained.

6. Estimate rating curves used for calibration for the other stream gaging stations interior to the pools from observed stages and from the computed flow of step 2.

7. Simulate water years 1965 and 1993.

8. Adjust the rating curves to achieve a better fit of observed stages.

9. Repeat steps 7 and 8 until the best reproduction of the observed stages is attained.

Rating curves can be used to calibrate the model to an accuracy of about 0.5 feet. In many cases the accuracy was somewhat greater. The shortcoming in rating curve analysis is not the procedure but rather the ability to adjust the rating curves using graphical editing on the computer. One simply cannot draw a rating curve on a computer to an accuracy of less than 0.5 foot.

10.1.3.3 Fine Tuning. To fine tune the model, calibration reaches were inserted between the principal gages. The tool for fine calibration was the discharge-conveyance change factors. For each calibration reach, a table of discharge and conveyance change factors was entered. A conveyance change factor for discharge Q_i is

$$F_i = \frac{K_{new}}{K_{old}}$$

where: F_i = conveyance change factor for discharge **i**.

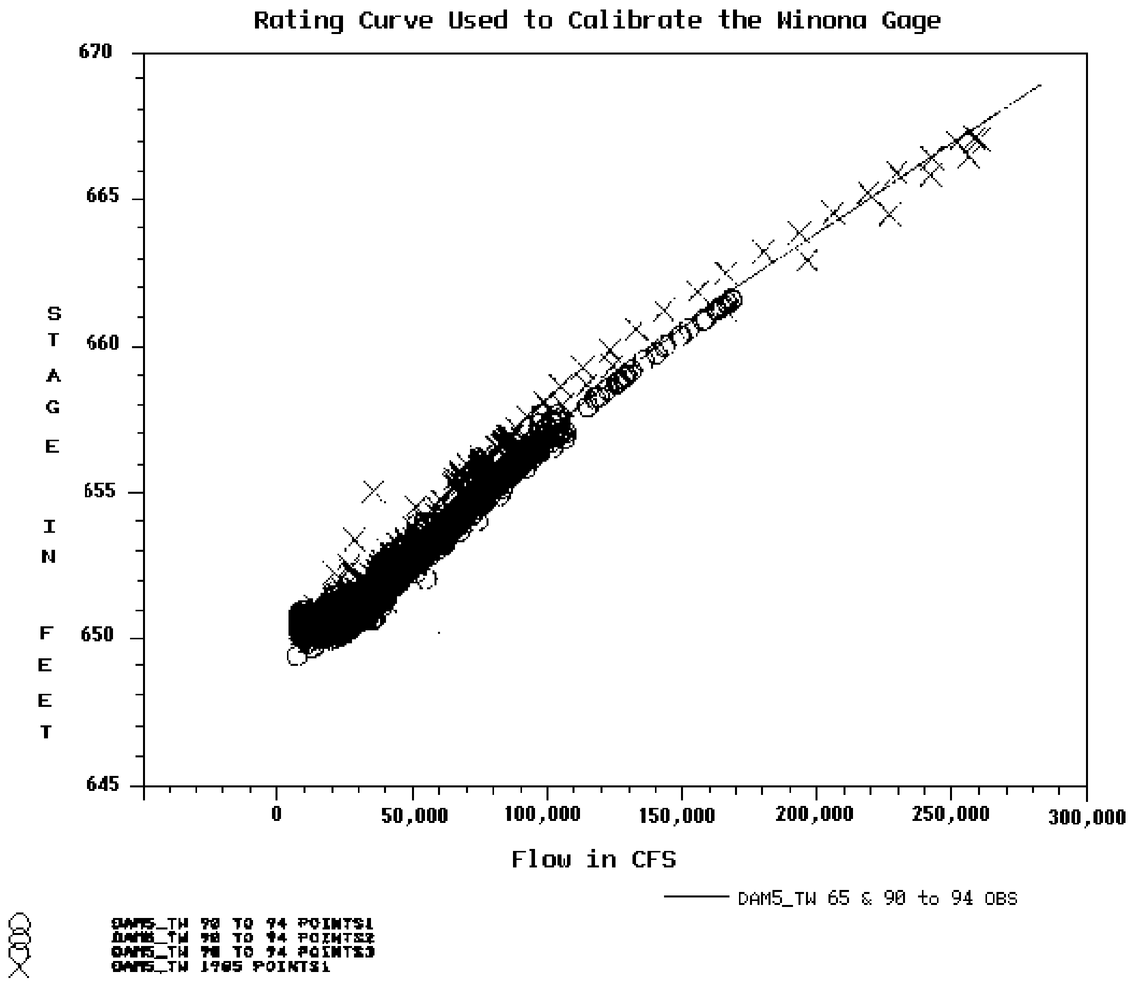
K_{new} = new conveyance value.
K_{old} = old conveyance value.

If the river discharge is Q_i, the conveyance property is multiplied by $F_{i,}$ thereby adjusting the calibration of the model.

For calibrating the model, discharge conveyance factors were primarily used to adjust the low flow reproduction in the pools when Mannings "n" becomes very small.

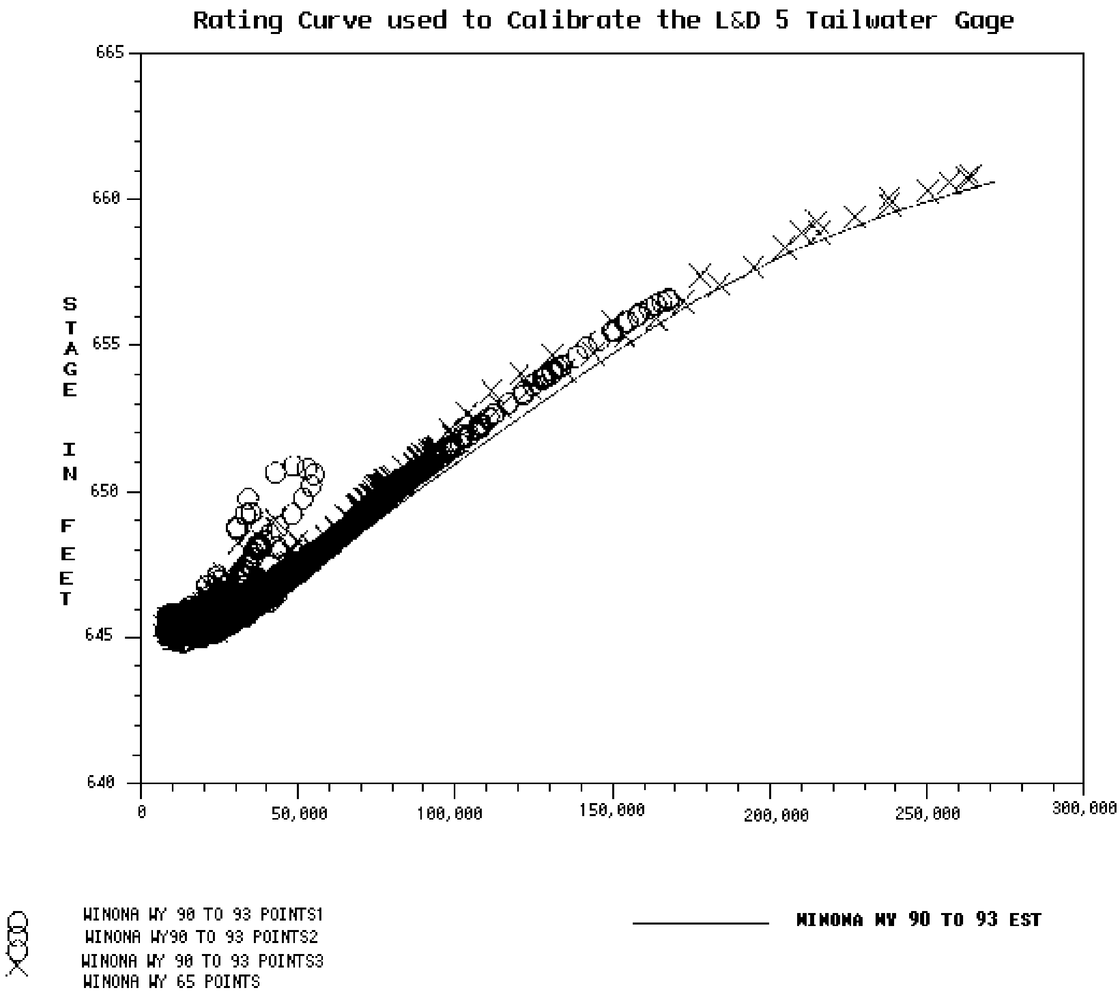
Since the river is carved from granular alluvium, the channel is constantly being reworked by the flow. Therefore, the river changes from year to year. While the Upper Mississippi River is very stable, one should expect changes on the order of tenths of a foot from one event to the next. In real time forecasting, the modeler would compensate for these changes using discharge conveyance change factors or using conveyance change factors.

Figure 10.1-7



Rating Curve Used to Calibrate the Winona Gage
670
665
660
655
650
645
STAGE IN FEET
0
50,000
100,000
150,000
200,000
250,000
300,000
Flow in CFS
DAM5_TW 65 & 90 to 94 OBS
DAM5_TW 90 TO 94 POINTS1
DAM5_TW 90 TO 94 POINTS2
DAM5_TW 90 TO 94 POINTS3
DAM5_TW 1965 POINTS1

Figure 10.1-8



10.1.3.5 Calibration-1993 Event. The model was calibrated to reproduce the stages and flow of water year 1993. Base calibration was from rating curves and fine calibration was through discharge-conveyance change factors. The model accurately reproduced stages at all of the stations except Brownsville where the stages appeared to be systematically one foot low. The model could not be adjusted to add that one foot of stage; therefore, one foot was added to the gage zero and the reproduction was acceptable.

Another problem was the computation of flow during the winter when the pools are covered with ice. The ice cover increases the wetted perimeter and the overall roughness of the cross-section; thus the computed discharge from the normal cross-section will be too large. The computed discharge at the gages during the winter is always greater than the USGS flow. One solution to this problem would be to use seasonal conveyance adjustment factors during the winter. As of this writing, the seasonal adjustments have not been tried.

10.1.3.6 Calibration-1965 Event. The 1965 flood was the flood of record on the Upper Mississippi River. The model was calibrated to reproduce high stages during the 1965 event. The calibration was accomplished by adjusting the upper part of the rating curves. The lower stages in the rating curves were not changed from the 1993 calibration. Still the model reproduced the lower stages to within .5 foot and the higher stages nearly exactly. The difference in the lower stages between 1965 and 1993 demonstrates the change in river morphology over the 28 year period.

10.1.3.7 Water Years 1991 through 1994. The model simulated the river water years 1991 through 1994. Inflow to the model was from USGS flow records. The simulation verifies the calibration of the model to within .5 foot of the observed stage and the overall stability of the Upper Mississippi River. The simulation also shows that the morphology of the river changes with time and that the forecast model must be fine tuned from year to year.

10.1.3.8 Forecast Period from 1995 to 1996. During the period from October 1, 1995 through July 31, 1996 the inflow from the model was computed by applying observed stage to rating curves at the tributary gages. This type of simulation simulates a real time forecast situation where USGS records are not available, and the modeler must estimate inflow from the stage record collected from the DCP (on site data collection platform). The stage record was of poor quality with numerous abrupt shifts, systematic errors, and long periods of missing data. However, the overall inflow was corrected using the null interior boundary conditions at St. Paul, Winona, and McGregor. The simulation was accurate with errors seldom exceeding .5 foot. Also, the errors were systematic which means that the error could be eliminated by fine tuning the model using discharge conveyance change factors.

10.1.3.9 Summary- Calibration and Forecast Simulations. The MBMS model was calibrated against water years 1993 and 1965 and verified against water years 1991 through 1994 and a period from October 1, 1995 through July 31, 1996. The model provided a nearly exact reproduction of stage for the calibration period. For the verification events, the model was within about .5 foot of the observed stage.

The simulations demonstrate that the model can adequately simulate the Mississippi River for forecasting. However, the river, which flows through alluvium, is constantly reworking its bed and the stage discharge relationship is changing from year to year. The calibration of the model must be updated to reflect these changes and to give the maximum accuracy.

Ice cover during the winter time increases the wetted perimeter and roughness of the river and undermines the accuracy of the null interior boundary condition. The null interior boundary condition computes flow from a stage hydrograph. The model, at present, assumes a free flowing river, even in the winter when the river is covered by ice; therefore, the null interior boundary condition overestimates flow. A routine must be devised to simulate the increased roughness of the ice cover.

10.4 Operational Experience. The St. Paul District MBMS UNET model was calibrated and tested with forecast simulations prior to the 1997 flood. During April 1997, the graphical user interface was installed so that the model could be used to forecast water surface elevations on the Mississippi River within the St. Paul District and also to provide the Rock Island District predictions at Lock and Dam No. 10. The 1997 flood provided a great opportunity to further develop the graphical user interface especially with regard to the features needed for the null boundary condition.

Experience during the 1997 flood indicated that the MBMS UNET model performed very well, especially once the crest occurred at the upstream end of the model. From that point on the simulation is essentially a hydraulic routing problem which UNET handles extremely well. Examples of the 1997 results are shown for St Paul, Minnesota, Lansing, Iowa, and Lock and Dam 10 at Guttenburg, Iowa.

As of now, the upstream boundary conditions for the MBMS UNET model are at Anoka, Minnesota and

Jordan, Minnesota on the Mississippi River and Minnesota River, respectively. For the upstream boundary conditions, the available National Weather Service predictions for the time of crest and the crest were used for extending the hydrographs to the end time of the time period. Extending the model farther upstream on the Minnesota and Mississippi Rivers could increase the performance of the UNET model especially in the vicinity of Minneapolis and St. Paul, Minnesota.

During the 1997 flood, the District's Construction-Operations Division needed forecasts in a timely manner with the final computed values adjusted so that the computed values match exactly with the observed values at the time of forecast. Typically, there is always a small error between the observed and computed values. The adjustment needed to make the computed values match the observed values is defined as the trend adjustment. To satisfy the needs of the St. Paul District's Construction Operations Division, the St. Paul District developed a dssmath macro that automatically makes the trend adjustment to the computed results. The results are then written to a postscript file and converted to GIF files which can be accessed through the St Paul District's Water Control Web Server home page. This approach requires about 20 minutes of time for a UNET forecast to be prepared with the graphical user interface. Once the results are available, the information is updated on the World Wide Web site. Graphical information from the St. Paul District's Water Control Web server MBMS Products page.

10.5 Interactions with Others. The St. Paul District's model starts at Anoka, Minnesota which is the furthest upstream boundary on the Mississippi River. Consequently, no input is needed from another district for the upstream boundary condition. For the downstream tributaries and boundary condition on the Mississippi River, the following is imported from the Rock Island District:

- Stage hydrograph for the Mississippi River at Dubuque, Iowa.
- Discharge hydrograph for the Turkey River at Garber, Iowa.
- Discharge hydrograph for the Grant River at Burton, Wisconsin

The St. Paul District exports the following to the Rock Island District:

- Discharge hydrograph for the Mississippi River at Lock and Dam 10.
- Tailwater stage hydrograph for the Mississippi River at Lock and Dam 10.

Comments regarding this project should be directed to: Stuart Dobberpuhl, P.E.
